TECHSAT 21 AND REVOLUTIONIZING SPACE MISSIONS USING MICROSATELLITES

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ABSTRACT

The Air Force Research Laboratory (AFRL) TechSat 21 flight experiment demonstrates a formation of three microsatellites flying in formation to operate as a "virtual satellite." X-band transmit and receive payloads on each of the satellites form a large sparse aperture system. The satellite formation can be configured to optimize such varied missions as radio frequency (RF) sparse aperture imaging, precision geolocation, ground moving target indication (GMTI), single-pass digital terrain elevation data (DTED), electronic protection, single-pass interferometric synthetic aperture radar (IF-SAR), and high data-rate, secure communications. Benefits of such a microsatellite formation over single large satellites include unlimited aperture size and geometry, greater launch flexibility, higher system reliability, easier system upgrade, and low cost mass production. Key research has focused on the areas of formation flying and sparse aperture signal processing and been sponsored and guided by the Air Force Office of Scientific Research (AFOSR). The TechSat 21 Program Preliminary Design Review (PDR) was held in April 2001 and incorporated the results of extensive system trades to achieve a light-weight, high performance satellite design. An overview of experiment objectives, research advances, and satellite design is presented.

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INTRODUCTION

Given recent advances in miniaturized electronics and micro-electromechanical systems (MEMS), 100kg microsatellites now can achieve comparable capability to 1000kg class satellites of 10 years ago. These next-generation microsatellites have a broad range of advantages that include low cost mass production, greater reliability, lower launch costs, and greater launch flexibility.

In 1995 the Air Force New World Vistas Space Technology Panel (Ref 1) advocated exploring the technical challenges and benefits of replacing large single satellites with formations of microsatellites to perform the same mission. In 1997 AFRL formulated a space mission concept (Ref 2,3) where reconfigurable formations of microsatellites with active RF antennas would form a multi-mission sparse aperture sensing platform (Fig 1). Key challenges include precise intersatellite metrology and signal processing for sparse aperture operation and autonomous formation control.
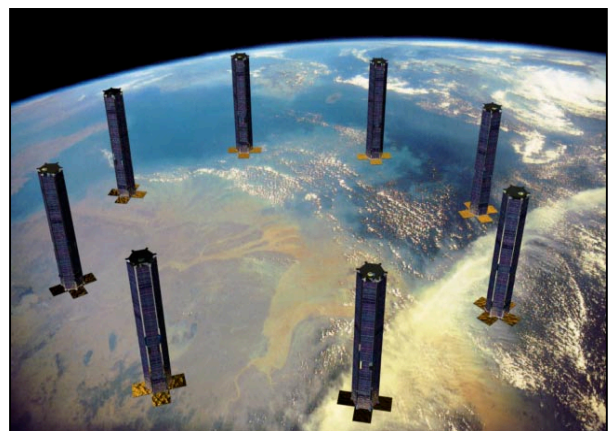

Figure 1. Sparse Aperture Formation

Advantages enabled by this concept include unlimited aperture size and geometry as well as flexibility to augment formations when and with as many satellites as desired. Tasking for alternate missions can be different

for satellites within a single formation or across the on-orbit system to tailor mission capability to changing global threat conditions. As individual satellites are replaced over the life of the system, improved sensing and computational capability of these advanced satellites continually augment baseline performance of the on-orbit system. Having multiple satellites also improves system reliability and allows continued operation in the event of individual satellite failure. Spatial separation improves system survivability to natural and man-made threats. In addition to configuring local formations to optimize a specific mission, the distribution of microsatellites within an orbital plane can be adjusted between formations to achieve continuous coverage or to increase the number of satellites in individual formations for improved capability. The low cost launch of small satellites facilitates both system upgrades and quick-response surge capability to augment monitoring of specific areas of interest.

In a 1998 Aerospace Corporation Conceptual Design Center (CDC) leveraged a system trade of different space-based GMTI concepts (Ref 4) to analyze a system comprised of microsatellite formations. This analysis verified performance viability of the concept and demonstrated life cycle cost savings of at least 50 percent over a system of large satellites. Further, the system of microsatellite formations had much greater flexibility and could perform a broad range of additional missions. It is anticipated that future high performance, affordable hybrid systems will exploit the strengths of large national assets with the added flexibility of microsatellites.

EXPERIMENT DESCRIPTION

To address the technical challenges of microsatellite formations and quantify mission performance, AFRL formulated the TechSat 21 flight experiment consisting of three 150kg satellites in a 550km orbit (Fig 2). Key program objectives are to demonstrate:

1) Autonomous formation maintenance and reconfiguration of 3 satellites in non-linear formations.

2) Sparse aperture sensing for multiple missions using innovative waveforms and signal processing.

3) Validated simulation with performance modeling for broad range of missions and satellite configurations (microsatellite formations, single large satellites, and hybrid systems in any quantities and orbits) to support future system architecture trades.

Autonomous Formation Flying

The satellites will initially be deployed from the launch vehicle in an along-track configuration separated by approximately 5km. During satellite initialization and on-orbit check out, the satellites will maintain this simple linear configuration with safe separation and no autonomous formation flying. After verifying basic GPS metrology measurements to 10m absolute position knowledge, very basic autonomy will be initiated to maintain the formation, first through monitoring of on-orbit generated command scripts and then with autonomous on-orbit execution of those scripts.
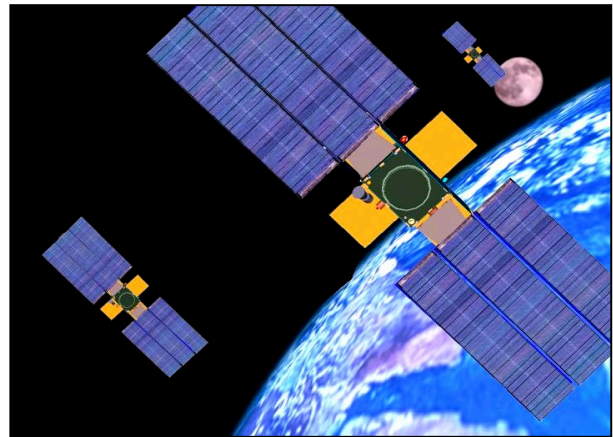

Figure 2. TechSat 21 3-Satellite Formation

Sparse aperture sensing experiments will be initiated during this slow progression of increasing autonomy, and satellite separation will slowly decrease over the next several months until reaching 100-500m relative distance. The satellites will then move into elliptical 3-D Hill's formations where the satellites have very slight variations in altitude, inclination, and eccentricity to produce the effect of the satellites rotating around a virtual point at their center. The size of this initial circular formation will be made as large as possible to achieve an acceptably low risk of collision while not so large that excessive fuel is required to transition from the linear formation to the Hill's formation. In these close formations, autonomous control is essential, and fail-safe separation algorithms (perhaps as simple as no thrust maneuvers) will be automatically executed if the satellite proximity falls below specific thresholds. The 3-D formation allows 2-D sparse aperture experiments to begin, and the separation of the satellites will be slowly increased in the Hill's formation until the 5km separation is again reached. At this time near the end of the 1-year experiment, the satellites will again return to closer formations to perform such higher risk experiments as autonomous formation reconfiguration and sparse

aperture sensing experiments at distances under 100m separation.

Position control of the satellites is baselined at 10% of the separation distance. The larger the error box in which each satellite must stay over successive orbits, the fewer orbit corrections and associated fuel required. This error box should be sufficiently large to allow relative displacements due to gravity perturbations so that fuel is expended on long-term formation maintenance rather than countering short-term natural periodic orbit variations. Small formations under 100m will have much tighter position control parameters and will expend more fuel for both long-term maintenance and for countering periodic variations in single orbits. Metrics for formation flying performance are speed of formation reconfiguration and fuel required for formation maintenance and reconfiguration.

Sparse Aperture Sensing

To enable sparse aperture operation (Fig 3), the first step is to verify operation of the intersatellite metrology system. GPS will provide absolute timing to ±100nsec, differential GPS will provide relative position knowledge of ±10cm and timing to ±20nsec, and an ultra stable oscillator will provide local time precision of ±5psec over the maximum signal integration time of 5sec. Intersatellite communications will regularly update position and timing measurements, and on-board extended Kalman filters will maintain best estimates of absolute and relative time and position. Prior to data collects, a series of payload synchronization pulses will improve relative position knowledge and timing an order of magnitude to ±1cm to ±50psec, respectively. The on-orbit requirement for relative timing is ±200nsec to synchronize payload transmissions from the three satellite payloads for sparse aperture sensing. The higher precision measurements are used in time interval correlation extended Kalman filter post-processing to align phase information to within one wavelength (±3cm) so that signal processing techniques can coherently align the sensor data from the three satellite payloads within 1/20 of a wavelength (±1.5mm) to create a single image from the three satellite "virtual aperture."

While the satellite formations slowly evolve over time, a broad variety of waveforms and sensor modes will be tested against numerous mission applications. When the full suite of sensing experiments are complete, sensing performance will be characterized for the complete range of formation geometries, sizes, clutter environments, and mission applications.

Experiment performance for different mission applications is expected to vary based on satellite separation. For example, large satellite separations are better for geolocation, bistatic synthetic aperture radar (SAR), and interferometric SAR (IF-SAR), and close proximity formations better for vernier on transmit SAR and GMTI. In addition to baseline sensor characterization, there will be numerous cooperative experiments with ground emitters and bistatic aircraft transmits and receives.
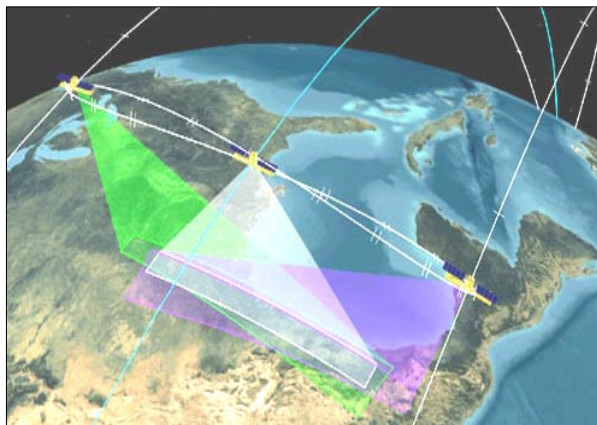

Figure 3. TechSat 21 Sparse Aperture Sensing

The payload on each satellite is an X-band (10 GHz) 2.0m^2 2-D electronically steered antenna (ESA) that transmits 175 watts effective radiated power. Basic sparse aperture sensor operation consists of the three satellite payloads forming three independent receive and transmit phase centers. Each satellite payload transmits distinguishable signals (frequency, coding, or other), and each satellite receives their own return plus the returns from the other two satellite payloads. Each payload will be capable of independent SAR image formation in addition to sparse aperture operation. This provides a performance reference for both conventional and distributed operation. This stand-alone operation will also be useful in the event of payload anomalies to help isolate which spacecraft has degraded performance. Sparse aperture modes of operation and the position and timing requirements discussed previously generally apply to SAR and GMTI. Such applications as geolocation have entirely different transmit modes and timing sensitivities. Each sensing mode, whether for the same or different mission applications, will have entirely different waveforms and signal processing algorithms. Given the broad range of sensing experiments, a subset of baseline waveforms and signal processing algorithms will be developed by AFRL, and the balance of experiments will be designed and post-processed by various customer organizations.

Planned sensing modes (Fig 4) include vernier on transmit SAR, single-pass interferometric SAR (IF-SAR), bistatic SAR with aircraft, along-track displaced phase center antenna (DPCA) GMTI, sparse aperture GMTI, bistatic space-time adaptive processing (STAP) GMTI, electronic protection from interference sources, time delay of arrival (TDOA) geolocation, frequency delay of arrival (FDOA) geolocation, secure communication, tactical downlink to theatre, and cross cueing between signal detection/geolocation and fixed target imaging.

Multi-static RF Imaging   GMTI of Tactical Targets

Secure Comm   Anti-jamming

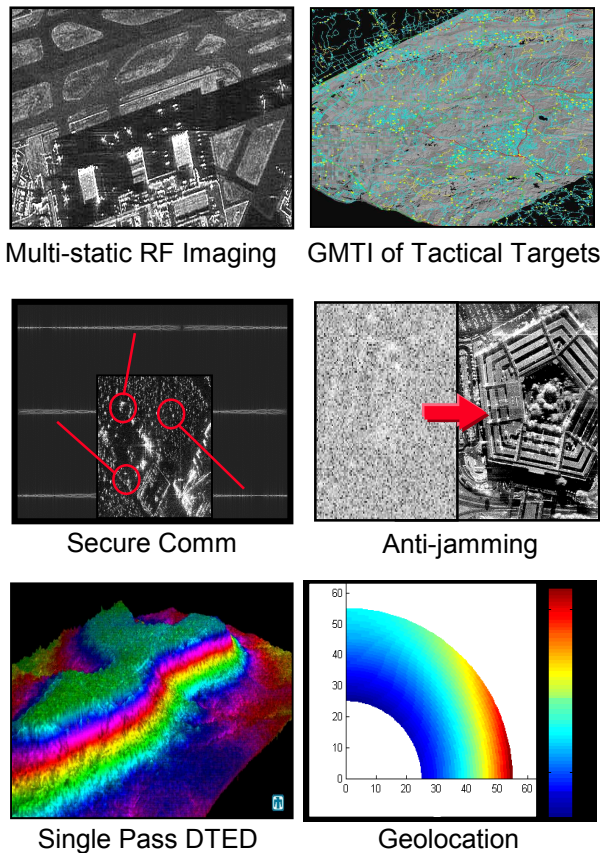Single Pass DTED   Geolocation

Figure 4. Example Sensing Experiments

Multi-mission RF sensing satellites offer very exciting possibilities for performing a broad range of mission applications in future systems. It is important to note that the 3-satellite TechSat 21 flight experiment is not designed to provide this operational capability but rather to demonstrate technical feasibility of the concept. TechSat 21's RF sensing experiments will record raw payload data to mass memory for downlink to the ground and subsequent data calibration and signal processing. Specific operational issues to be addressed in follow-on flight demonstrations include high performance processors for on-orbit signal processing, operational target detection algorithms, data dissemination to operational systems, adequate power aperture for operational area coverage and revisit rates, and broadband RF antenna technology.

Modeling and Simulation

A key flight experiment objective is to generate experimental data for validation of operational mission performance models. AFRL's Distributed Architecture Simulation Laboratory (DASL) testbed will be expanded throughout flight experiment development and on-orbit operations to model performance metrics for a wide variety of potential missions. The flight experiment sensing performance will refine those models with regard to such variables as clutter background, sparse aperture transmission sidelobes, ambiguity sources and magnitudes, ionospheric effects, as well as other variables. By completion of the flight experiment, the DASL testbed will be able to run realistic system architecture trades that can compare such metrics as area coverage rates and probability of detection for systems composed of single large satellites, microsatellite formations, or hybrid systems in any quantities at any altitude.

This testbed is also performing critical roles during the research and satellite development stages. All formation flying, autonomous control, and signal processing algorithms provided by a broad range of research organizations are loaded into the testbed for performance validation prior to incorporation into flight software or experiment command scripts. Further, the testbed supports numerous satellite design trades of which just a few include evaluating payload antenna size against experiment performance, performing sensitivity analyses of position accuracy and its effects on various sensor modes, and sizing the propulsion system in terms of bit impulses and total fuel requirement.

The DASL testbed is extremely flexible and can operate interactively in real or regimented time and can perform both parametric and Monte Carlo evaluations. The data center warehouses both simulation and experimental data and supports mining of archived information by both on-site and remote customers. The central challenge was to efficiently manage simulation interactions and data flow with existing codes and programs written across multiple languages and environments. This was achieved by leveraging an existing simulation architecture called the Spacecraft Simulation Toolkit (SST) with direct socket connections into an integrated database.

ENABLING RESEARCH

Formation Flying

The first critical challenge was to identify natural orbits that maintain satellite formation without continual thrusting. The relative motion of multiple satellites can be solved from Hill's equations:

$$\ddot{x} - 2\omega\dot{y} - 3\omega^2 x = f_x$$

$$\ddot{y} + 2\omega\dot{x} = f_y$$

$$\ddot{z} + \omega^2 z = f_z$$

These equations describe relative motion of two orbiting bodies in close proximity to one another and in nearly circular orbits, where ω is the orbital frequency for the reference satellite, (x,y,z) are (small) displacements of the "chase" satellite's position relative to the reference, and (f_x,f_y,f_z) are externally applied forces in the (x,y,z) directions, respectively, as shown in Figure 5. The x direction is radial from the center of the Earth to the reference satellite, y is orthogonal to x in the orbital plane of the reference satellite and in the same sense as the velocity vector, while z is normal to the orbital plane and completes right-handed triad.
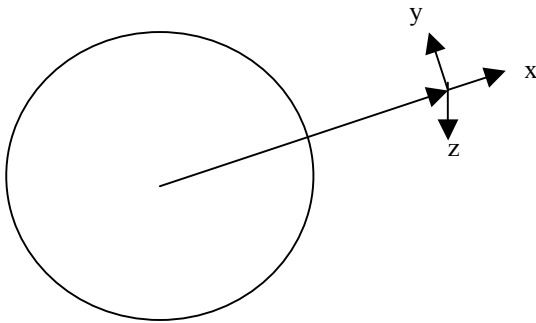

Figure 5. Hill's Frame of Reference

Numerous research efforts have identified formation initialization and control strategies that significantly reduce fuel requirements for formation maintenance and reconfiguration. Kong et al. (Ref 5) used a baseline mission at a polar 800km orbit and quantified perturbations due to gravity, atmospheric drag, solar pressure, and electromagnetic force. They demonstrated that gravity perturbations have the largest effect and that the very large ΔV requirements make non-Keplarian orbits unrealistic. Sabol et al. (Ref 6) showed the earth's oblateness term, J_2, to be the major gravity perturbation term causing formation dispersion. Mean elements were identified as a key variable in designing and controlling formation since they improve insight into long-term behavior by eliminating short-term periodic effects. Schaub and Alfriend (Ref 7) identified formation solutions unaffected by J_2 perturbations which enforced two constraints on the satellites in formation: 1) equal nodal periods and 2) equal latitude rates, $d/dt(l+g)$, in Delaunay variables, where l is the mean anomaly and g is the argument of perigee. This enabled selection of formation initial conditions to reduce long-term fuel requirements by an order of magnitude. Vadali et al. (Ref 8) formulated and solved initial condition determination and fuel optimal control problem for formations with out-of-plane motion and also considered both impulsive and continuous propulsion systems. Inalhan, Busse, and How (Ref 9) showed real-time 2-5cm position accuracy using a Kalman filter to estimate carrier-phase differential GPS integer biases and a separate Kalman filter subsequently estimating relative positions.

Autonomous Formation Control

Princeton Satellite Systems' ObjectAgent and Interface & Control Systems' Spacecraft Command Language (SCL) provide on-board autonomy (Ref 10) to fly within specified parameters, avoid collisions, perform fault detection, isolation, and recovery (FDIR), and plan and schedule activities. To create a "virtual satellite," ObjectAgent provides agent-based, object-oriented on-orbit distributed flight control framework, and SCL provides software infrastructure and on-board expert system for formation commanding, health-and-status monitoring, and FDIR.

Signal Processing

The key focus of this signal processing research is to develop novel waveform and processing approaches that exploit the added degrees of freedom of a spatially diverse formation, maximize system information content, improve mission performance, and resolve inherent ambiguities of a sparse aperture system. Note however that experiment success is not dependent on these techniques, since baseline sensing performance will be validated using standard bistatic, IF-SAR, and STAP signal processing techniques. One innovative approach being explored by Garnham et al. (Ref 11) is vernier on transmit which uses separate frequencies within the available transmit bandwidth to avoid transmission grating lobes. Since transmission gain is decreased, larger spot illumination produces increased range/Doppler ambiguities. This is compensated by transmitting orthogonal codes sequentially in time, using a pulse compression approach that deconvolves

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the signal, to resolve these range/Doppler ambiguities. Another possible variation on this approach uses nulling beamforming techniques to spatially null range/Doppler ambiguities and hence enable larger viewing geometry for SAR image formation.

An entirely different approach to performing space based GMTI by Marais et al. at MIT exploits radar interferometric processing. A Scanned Pattern Interferometric Radar (SPIR) algorithm uses the high angular variability of a sparse array Point Spread Function (PSF) to collect sufficient data from the signal return so that clutter and targets can be separated without a priori assumption of the clutter statistics. They show that the deterministic geometric relationship between observation direction and clutter Doppler shift enables targets within the main lobe of the individual aperture pattern to be separated from the clutter. If the computational domain is extended to the side lobes of the gain pattern, clutter entering through these lobes can also be extracted.

SATELLITE DESIGN

In addition to the innovative concept of sparse aperture operations and the innovative research in formation flying and signal processing to enable it, two key objectives of the satellite design were to keep the mass as close to 100kg as possible and to keep the cost as low as possible. To do this, the spacecraft leverages numerous development programs for advanced, lightweight subsystem at AFRL, DARPA, JPL, and NASA Goddard. This has enabled a very capable satellite (Fig 6) with a mass of 150kg and with an approximate cost per satellite of $17M for bus and payload design, fabrication, and test.

In the stowed configuration for launch, the dimensions of each satellite are 1.1m x 1.1m x 0.8m. With the thin-film solar arrays unfolded, the satellite dimensions become 7.8m x 2.3m x 0.8m. The current best estimates for the satellite mass is 150kg with 65kg for the payload and 85kg for the bus. The prime contractor for the satellite design, fabrication, and test is MicroSat Systems, Inc. in Denver CO.

Command and Data Handling (C&DH)

The C&DH subsystem is being developed by BroadReach Engineering and consists of a 133MHz Rad 750 processor with 128MByte RAM and 256KByte EEPROM. It uses compact peripheral component interconnect (cPCI) for synchronous 32-bit data transfer at 33MHz. There are four 3U boards: flight processor, communications and payload interface,

state of heath monitor and attitude control interface, and power conversion. The C&DH box is composite on an aluminum baseplate for a total weight of 3kg for the C&DH unit. Its average operating power is 30 watts. The C&DH has a RS-422 interface to an external 160GByte mass memory unit comprised of mass memory controller board, mass memory power board, and eight 20GB hard drives (required to support 160Mbps data rates during payload operation). The mass memory unit weighs 3.1kg and requires 80 watts power. The C&DH also links to an external ultra-stable oscillator for local and intersatellite timing synchronization to support sparse aperture payload operations.
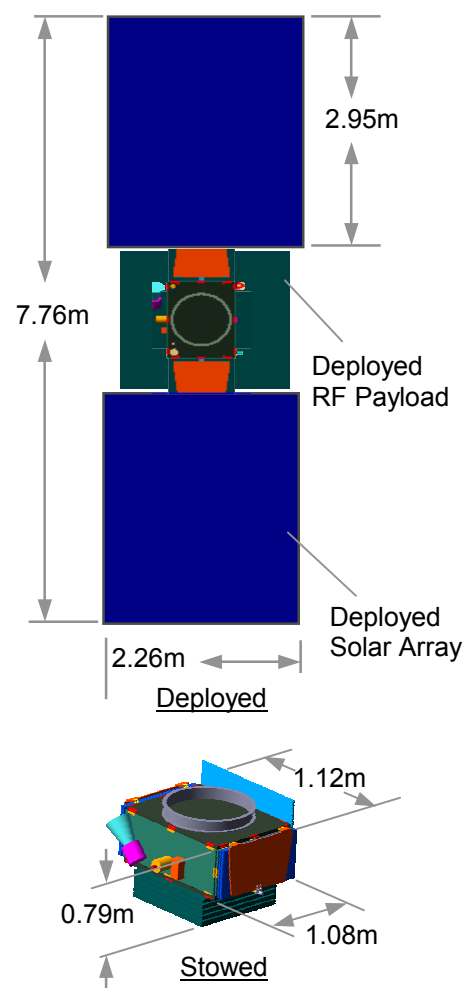
Figure 6. TechSat 21 Satellite
(Stowed & Deployed Configurations)

C&DH provides computing support for command and telemetry data, attitude determination and control, navigation, formation control, thermal control, payload

commanding, data transfer, mass memory management, and spacecraft timing calculations.

Attitude, Determination, and Control (ADAC)

The ADAC subsystem is being developed by Advanced Solutions Inc. and implements attitude determination using one 3-axis magnetometer, three 4-head analog sun sensors, and one star tracker (Fig 7). Nominal operation requires no more than 2.5 degree attitude knowledge, and payload data collects achieve

Figure 7. Ball CT-633 Star Tracker

the required 0.05 degree attitude knowledge using the star tracker. Three-axis attitude control (Fig 8) to 0.5-1.0 degree is achieved with three 1.0N-m-s reaction wheels and three magnetic torque rods. Primary modes of operation are: maintain sun pointing of solar arrays for power collection, point payload antenna at nadir
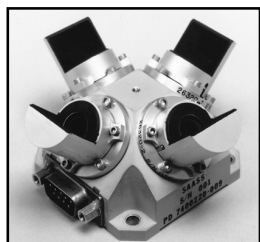
Adcole Sun Sensors
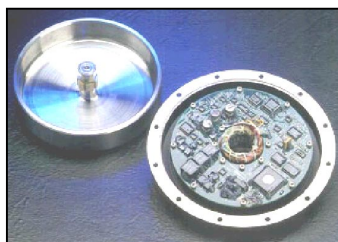
Ball 1N-m-s Reaction Wheels

Billingsley TFM-100S Magnetometer

Zarm MT-15-1 (15 A-m^2) Torque Rods

Figure 8. ADAC Subsystem Components

during eclipse for thermal management, point payload antenna for data collects, point spacecraft for delta-V maneuvers, and support initialization and safe mode operations.

Electrical Power

The electrical power subsystem (Fig 9) consists of thin-film solar arrays using copper indium gallium diselenide (CIGS) on stainless steel substrate. The two solar arrays have a total area of 12.8m^2 and provide 900 watt power output at 8% efficiency (BOL). The total mass of the arrays with deployment booms is 11.2kg. An 8-cell lithium polymer battery provides 1500 watt-hours (48 amp-hours) at 60% depth of discharge to support 660 watts on-orbit average power with peak power of 2900 watts for durations of up to 10 minutes. The battery weighs 8kg and the power control electronics comes to an additional 3kg.

Thin-Film Solar Array   Lithium Polymer Battery

Figure 9. Electrical Power System

Propulsion

Each satellite has a single 200 watt Hall effect thruster (Fig 10) being developed by TRW that provides variable 5-10 N-m thrust, 1300 sec specific impulse, and 35% efficiency. The dry mass of the thruster, electronics, and fuel system is 7kg, and 1kg of Xenon fuel provides a total of 65 m/s delta-V for each spacecraft. This is sufficient for 1 year operation that includes formation initialization, maintenance, and several reconfigurations between 5km formations to smaller 100m formations and from linear to non-planar elliptical formations.
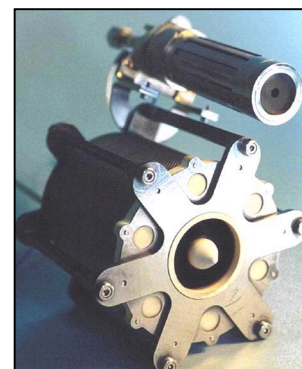

Figure 10. 200 Watt Hall Effect Thruster

Communications

Alternative approaches are under consideration for intersatellite communications and telemetry, tracking and command (TT&C). One combines a Ku-band intersatellite transceiver and GPS receiver system with an off-the-shelf TT&C system. A different integrated system has S- and L-band receive, S-band transmit, and GPS receive. In this system the S-band supports both intersatellite communications and TT&C. Relatively low data rates of 128bps are used for intersatellite communications to pass position and timing information to support both formation flying and sparse aperture payload operations. The TT&C data rates are 100kbps uplink and 1Mbps downlink. High bandwidth downlink of experiment data uses the X-band payload antenna. The mass of the TT&C, GPS, and intersatellite communications system is expected to be 2.5-3.5kg.

RF Payload

The payload is an X-band (10GHz) 2.0m^2 2-D electronically steered antenna (ESA) with true time delay steering and effective radiated power of 175 watts. The current best estimate of the mass including antennas, remote electronics unit (REU), support structure, and deployment hinges is 65kg. The payload has a single channel receiver with a programmable waveform generator. Most of the REU boards are modified for space operations and environment from existing F-16 antenna receiver/exciter control electronics. The payload will also provide high bandwidth communications downlink at 160Mbps to commercial X-band satellite ground stations. Two minutes of payload operation generates 40GHz of sensor data. Under normal operations this data will be downlinked over a period of 3-4 days but could be downlinked in a single day at existing ground sites if it were a high priority. Maximum payload power use during experiment operations is 1500 watts for 2 minutes, and nominal payload power use during communications downlink is 700 watts for contact periods of up to 10 minutes.
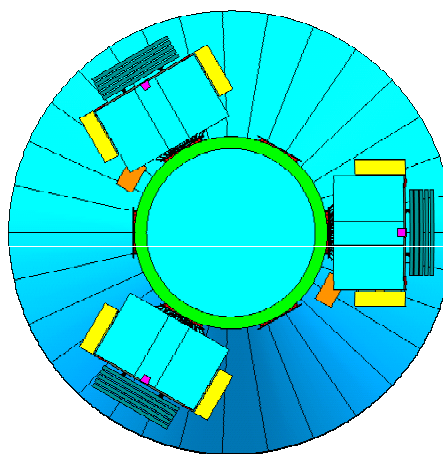
Launch Vehicle

The baseline launch vehicle (Fig 11) for the 3 TechSat 21 satellites is the EELV Secondary Payload Adapter (ESPA) ring on the Evolved Expanded Launch Vehicle (EELV) launch currently scheduled for Oct 04. The launch vehicle, launch vehicle integration, and on-orbit operations are provided by the DoD Space Test Program Office. The mass estimate for the 3 satellites with margin and separation systems is 540kg.

Risk Mitigation

The TechSat 21 satellites are being designed as Class D using extensive risk management rather than traditional risk avoidance. The approach is to perform thorough component-level and system-level testing throughout development and integration. By the time the satellites launch, aircraft flight tests will have proven out waveform design and signal processing approaches, and a full multi-satellite ground sparse aperture system test will have verified the satellite hardware and synchronized timing. Contingency modes enable a broad range of 3-satellite formation flying and RF sensing objectives to be accomplished even with the loss of one of the satellites (e.g., beacon mode on a failed satellite allows the other satellites to fly in formation). Potential restrictions on payload performance due to hardware failures or degradation in
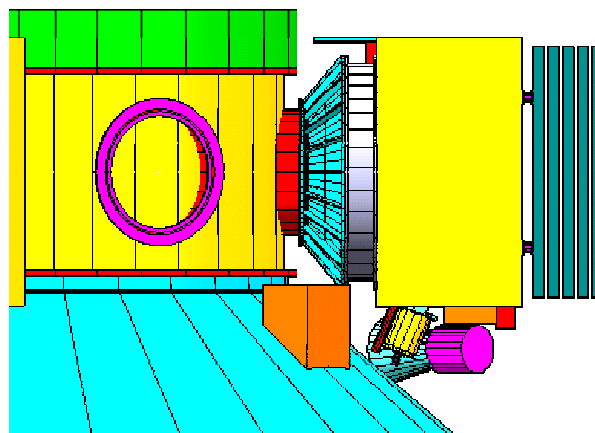
Launch Configuration on ESPA Ring

Three Satellites Mounted at 120 deg

Figure 11. TechSat 21 Satellites on Launch Vehicle

metrology and timing measurements have a broad range of contingencies that include use of strong point reflectors on ground targets and post-processing using advanced image co-registration techniques.

Sparing Policy

Given funding limitations which prevent sparing to the level desired, the following guidelines for the number of component spares minimize schedule impacts during flight hardware fabrication, integration, and test: 1-2 engineering development units (depending on the component test requirement), 3 sets of flight hardware, 3 sets of electronic ground support equipment, 1 hot bench, and 1 testbed.

Stringent mission assurance rules ensure proper handling and protection of flight hardware. For all long lead items, vendors will have the hardware, processes, and personnel to repair, retest, and return repaired components within 1 week of receiving damaged hardware. By design, no component will require more than 8 hours to remove and replace. All high value component suppliers will maintain rapid repair kits and begin work immediately upon receipt of a failed unit. This includes communication gear, star sensor, propulsion hardware, and flight processor. For the C&DH and power components, an extra set of flight hardware will be provided with the original build. This set of hardware can be delivered to the spacecraft within 3 weeks of notification. A complete spare of the flight battery will be maintained. At the time of system level environmental testing, high risk components will be identified and flight spares will be reconsidered given overall program status on cost and schedule. Although there will be no spare spacecraft, prudent component sparing should allow quick recovery to any subsystem failures through I&T.

CONCLUSION

TechSat 21 is a technology-push flight experiment that explores the technical challenges and multi-mission performance benefits of using formations of microsatellites to accomplish certain missions typically performed by larger single satellites. Microsatellites provide numerous advantages that include unlimited aperture size and geometry, ability of formations to tailor on-orbit system to changing global threat conditions, greater system reliability and survivability, and lower life cycle costs. These advantages can significantly augment the capabilities of the future U.S. space system architecture. The mission simulation testbed generated out of this flight experiment will have the capability to perform system architecture trades and

identify what quantities of microsatellites performing what missions adds the greatest performance at the lowest cost. Hybrid systems comprised of a combination of large and small satellites have great potential to exploit the strengths of large national assets with the added flexibility of microsatellites.

The TechSat 21 flight experiment completed its Preliminary Design Review (PDR) in April 2001 with the Critical Design Review (CDR) scheduled for February 2001. The 3 satellites are planned to be launch ready by July 2004 with one year of on-orbit operations. Key experiment objectives include demonstration of formation maintenance and reconfiguration, autonomous formation control, and multi-mission sparse aperture sensing. Assuming successful demonstration of the utility of microsatellite formations, a follow-on flight demonstration will be required to address such additional challenges as on-orbit processing, area coverage rates, target detection algorithms, and broadband RF antenna technology before the concept is sufficiently mature for operational systems. The Air Force Chief Scientist and the Air Force Scientific Advisory Board have been very strong advocates of the TechSat 21 program and other flight experiments exploring revolutionary, high-payoff space mission concepts.

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